

## Observations of Natural ELF and VLF Electromagnetic Noises by Using Ball Antennas

Toshio OGAWA, Yoshikazu TANAKA, Teruo MIURA, and Michihiro YASUHARA

Geophysical Institute, Kyoto University, Kyoto

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### Abstract

A simple observing system for the measurements of vertical electric field component of natural ELF and VLF electromagnetic noises by using ball antennas is described. With this system it is possible to measure long traveled natural ELF noises discriminated from natural local noises due to such as atmospheric electric space-charge fluctuations. Some of the typical recorded noises are shown. Observed ELF noises are divided into three characteristic types; "ELF flash", "ELF burst" (N-and Q-types), and "ELF continuous". ELF flashes originate from the lightning discharges in the area within about 1,000 km from the observing station. Occurrences of ELF bursts are more frequent in the daytime than in the nighttime, and are characterized by sudden increase at the time of local sunrise, suggesting the related mechanism of their generation to the solar position relative to the earth. N-type bursts are followed by VLF noises. Source distances of these bursts which are followed by tweek-type atmospherics in the night are estimated to be in the range from 2,500 km to 5,000 km. Q-type bursts often show clear oscillations of the frequencies of Schumann resonances. The daily variations of the mean amplitude of "ELF continuous" which composes the background noises are quite similar to the daily variations of the world thunderstorm activity.

### 1. Introduction

In recent years a number of workers have investigated natural ELF phenomena in the electromagnetic waves from different points of interests. Some workers are interested in the study of propagation of ELF radio waves from distant lightning discharge as a source. Other workers are interested in the study of the relation of ELF noise origin to the world-wide thunderstorm activity. Since Schumann (1952 a, b, 1957) presented the resonance theory that ELF electromagnetic waves resonate in the cavity between the good conducting earth and ionosphere, a number of experimental investigations were made to detect actual resonant frequencies in natural electromagnetic phenomena (Balser and Wagner, 1960; Polk and Fitchen, 1962; Chapman and Jones, 1964; Gendrin and Stefant, 1964; Rycroft and Wormell, 1964; Hughes, 1964).

ELF phenomena, however, do not seem to be completely understood, because the typical recorded noises shown in the literatures are not consistent with each other. Some workers recognized that the resonated signals are hidden in the background noises and they appear only by frequency analysis of measured noises (Balser and Wagner, 1960; Madden and Thompson, 1965), while some others clearly showed characteristic oscillations in the meas-

ured records (Polk and Fitchen, 1962; Polk, 1964; Hughes, 1964). They seem to have concerned apparently with different phenomena. It might come from the differences of sensitivities and frequency responses of the instruments which they used.

In the literatures three major types of method of measurements are reported; the measurement of electric field, magnetic field (Polk, 1964; Gendrin and Stefant, 1964), and earth current (Sao, Jindo and Yamashita, 1963). In the measurement of electric field component, the vertical or horizontal antenna is usually used. For example Balser and Wagner (1960) used the high tower of 37 m in height, while Rycroft and Wormell (1964) used the horizontal antenna of 190 m in length. Chapman and Jones (1964) used the 3 m vertical rod antenna, and Hughes (1964) used the vertical whip antenna of 10 m in length. The present measuring system reported here includes a simple type of capacitive conductor antenna which is called the "ball antenna".

In highly populated area the atmospheric electrostatic field is largely disturbed and there occur many fluctuations of various short periods. The ELF range fluctuations would possibly associate with them. This is one of the reasons why it is difficult to measure ELF electromagnetic waves in large cities. Other disturbing factors are artificial noises from nearby electric power lines, and noises from leakage earth current from street cars or big factories.

The power spectrum of the atmospheric electric fluctuations is not completely known and may have continuous component in the concerned frequency range so that it is difficult to prevent the effect of such noises. Because of the definite frequency of the power-line noises, on the other hand, they can be excluded by using suitable filters.

In the present study natural ELF electromagnetic noises were measured by multi-antenna system with enough sensitivity in wide frequency range, being discriminated from undesirable noises in a large city.

## 2. Measuring Principle and Apparatus

In the measurement of long traveled ELF electromagnetic waves the electric field near

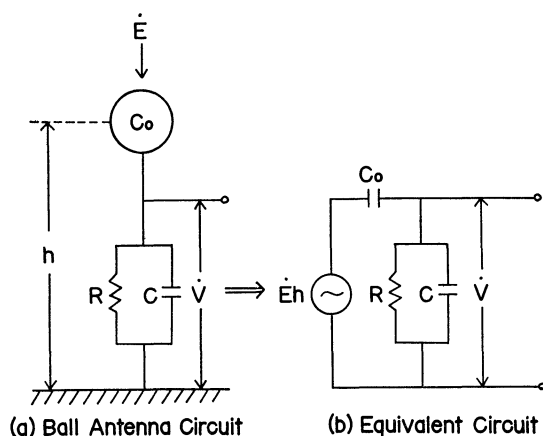


Fig. 1 The ball antenna circuit and its equivalent circuit.

the plane ground would reasonably be vertical and constant. Suppose  $\vec{E}$  is the electric field strength expressed in complex. When a conductor of capacity  $C_0$  is raised in the air to a height  $h$  from the ground surface and connected to the ground through a resistance  $R$  and a capacitance  $C$ , it receives the electric potential variations at that level (Fig. 1 (a)). The equivalent circuit of this antenna is given by Fig. 1 (b), where  $\vec{E}h$  is the generator voltage and  $\vec{V}$  is the output

voltage which should be fed to the grid of an amplifying tube. A simple calculation shows that the amplitude of this voltage,  $V$ , is proportional to the amplitude of  $\dot{E}$ ,  $E$ , and given by

$$V = \frac{\omega C_0 R}{\sqrt{\omega^2 R^2 (C_0 + C)^2 + 1}} E h \quad (1)$$

where  $\omega = 2\pi f$  and  $f$  is the frequency.

As the size of the conductor antenna cannot practically be far from a few decimeters in the diameter, the value of  $C_0$  become the order of ten  $\mu\mu F$ . Therefore,  $V$  become to depend largely on the value of  $C$ . If, as is usually done, the coaxial cable is used to connect the antenna to the amplifying circuit, some hundred  $\mu\mu F$  are easily needed for the value of  $C$ . Therefore an impedance transformer using a cathode follower was put into the empty conductor can. The grid of the electrometer tube 5886 is connected to the inside of the can to minimize the value of  $C$ , and the can is supported by a teflon bar which is protected by a metal cover from the ambient polluted air. A resistor of  $1 \times 10^9$  ohms is used as a grid leakage resistance, which was also put into the can. The frequency response of the antenna calculated using equation (1) is shown in Fig. 2 for the input capacitance of  $2\mu\mu F$ , where gain loss is 7 db at

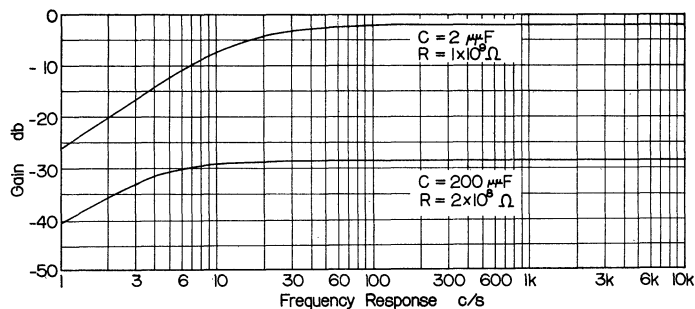


Fig. 2 The frequency response of the ball antenna. The capacity  $C_0$  of the ball antenna is  $8\mu\mu F$ .

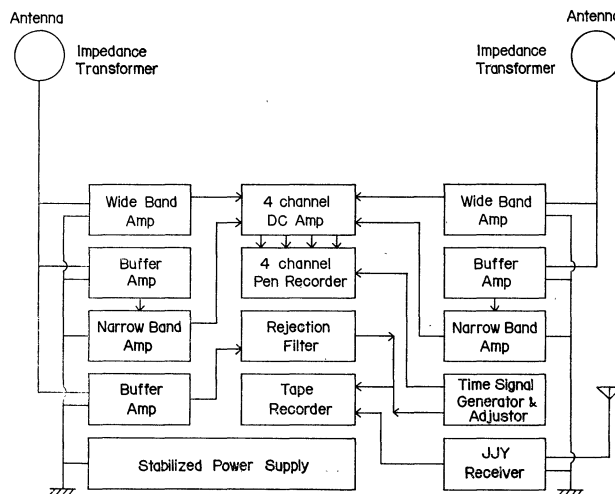


Fig. 3 ELF and VLF observing system.

8 c/s compared with at higher frequencies.

The whole system of the measuring apparatus is shown in Fig. 3. The output of the cathode follower is connected to three different frequency-response amplifiers, the first of which has the band width of 3-16 c/s ("narrow band") and the second 2-50 c/s ("wide band") (Fig. 4), decreasing the gain by 10 db, and the third 200 c/s-8 kc/s (VLF).

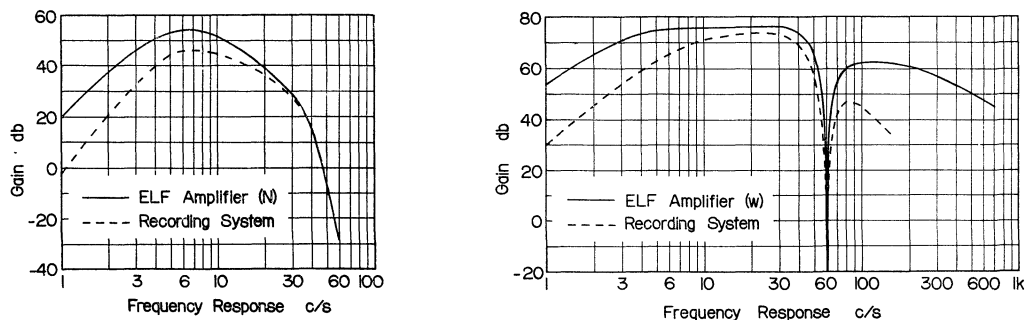


Fig. 4 The frequency responses of the narrow band ELF amplifier (N) and the wide band amplifier (W).

The chart paper of pen recorder ran at a speed of 1 mm/sec, and 25 mm/sec or 50 mm/sec.

In preliminary experiments ELF noises were measured for a certain period respectively at several height levels as changing the height of the ball antennas from the top of the building of the Geophysical Institute. Then measurements were made using two antennas as changing their separation from a few meters to 15 m. The separation of the antennas was increasingly extended to about 4 km in Kyoto city and finally to about 500 km. In the last case two antennas were placed separated by 15 m on the top of the building and the third antenna was placed at the Aso Volcanic Laboratory of Kyoto University in Kyushu.

The idea of this complicated procedure is that local noises such as the effects of atmospheric space-charge fluctuations would affect in much smaller area than long traveled electromagnetic waves do.

It is found in the experiments that local noises become acceleratively less with increasing height of the antenna, and with 15 or more meter separation between the two antennas local noises are received by both antennas simultaneously in a relatively small part of time, while with a few-meter separation both antennas receive same effects of local noises although phases are largely shifted from each other.

Finally two antennas of the height of 5.5 m were set on the top of the building of the Geophysical Institute separated from each other by 15 m. The height of the antenna from the ground surface is 20 m. With this measuring system natural ELF electromagnetic waves are received on at least either one antenna for the most part of non-precipitating day, even if local noises disturbed on the other.

### 3. Observations

After preliminary simultaneous observations at Kyoto and Aso in May 1965, continuous

observations were made from July 12 to August 31, 1965 at Kyoto and partly at Kyoto and Aso simultaneously. The measurements were made at 5, 6, 7 and 8, and 11, 12, 13 and 14 o'clock JST and were continued for 6 minutes every time. This program was originally made between the New Mexico Institute of Mining and Technology, Socorro, New Mexico, U.S.A., and the observation times correspond the occurrence times of New Mexico thunderstorms. As the both data are not examined together yet, the effects of the New Mexico thunderstorms are not investigated in this paper.

The simultaneous measurements were made at Wakkanai in Hokkaido, Kyoto, and Aso on September 22–23, 24–25 and 26–27, 1965. The distance from Kyoto to Wakkanai (the north end of Japan) is about 1,200 km. This is the maximum scale of observation which can be done in Japan. It was fair weather each day. The measurements were made from 12 h JST in the preceding day to 12 h JST in the next day. Both pen and magnetic tape recorders were operated for 6 minutes every hour from 12 h 00 m to 12 h 06 m, from 13 h 00 m to 13 h 06 m, and so on.

Other measurements were made at Kyoto on the same time schedule on December 10–11 and 14–15, 1965, and on March 26–27 and 29–30, and on May 8–9, 1966.

Some of the typical recorded ELF noises are reproduced in Fig. 5. Observed ELF noises are divided into three different characteristic types according to their amplitudes and wave forms; “ELF flash”, ELF burst (N- and Q-types), and “ELF continuous”.

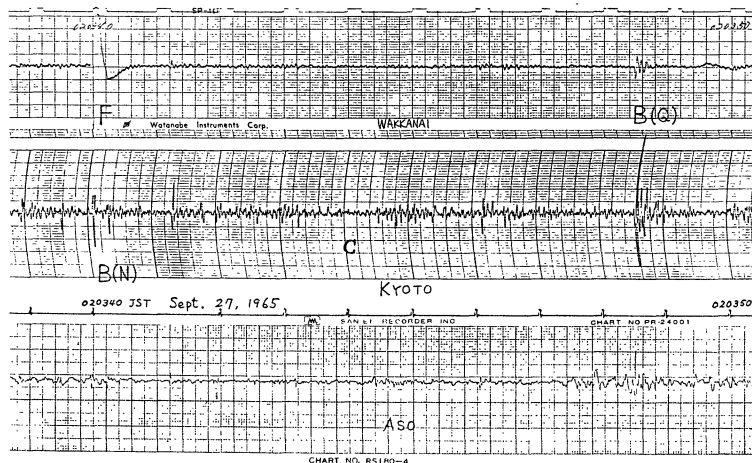


Fig. 5 Record sample of ELF flash (F), ELF burst (B, N: N-type, Q: Q-type) and “ELF continuous” (C) observed at Wakkanai, Kyoto and Aso on September 27, 1965.

#### 4. Results of Observations

1. “ELF flash”. In summer time characteristic simple, and rapidly damping wave forms were often observed as shown in Fig. 5, which were named ELF flashes. In the most cases the recording pen ran over full scale. They were found to be the effects of lightning discharges originating within about 1,000 km by the simultaneous measurements at Kyoto and

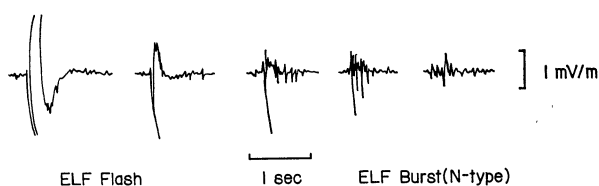


Fig. 6 Schematic illustration of transforming wave form of ELF flash to ELF burst.

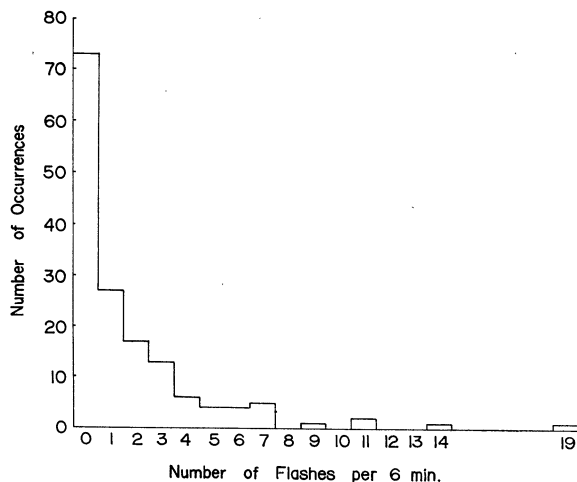


Fig. 7 Occurrence frequency of the number of ELF flashes per 6 minutes in July and August, 1965.

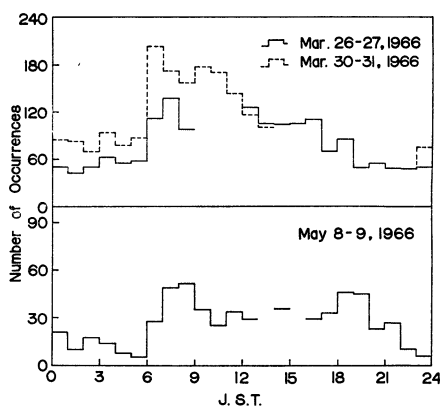
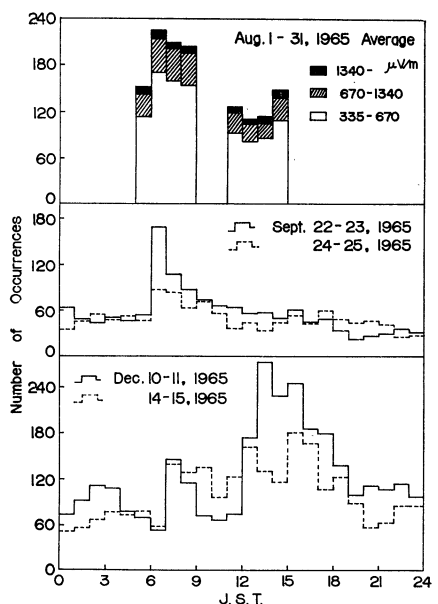


Fig. 8 Daily variations of the number of occurrences of ELF bursts counted for the bursts which had larger amplitudes than  $400 \mu V/m$  except August and May data. For May 8-9, 1966 were counted the numbers of bursts of larger amplitude than  $660 \mu V/m$ , which were recorded for three minutes.

Aso, and also at Wakkanai, Kyoto and Aso. The evaluation of source distances of some of ELF flashes were made by analyzing the frequency-dispersion characteristics of tweek-type atmospherics by which ELF flashes were followed (refer to Appendix). The changing wave forms are represented schematically with increasing distances from the left to the right in Fig. 6. It is shown in Fig. 6 that the ELF flashes are converted to ELF bursts in more than about 1,000 km.

The frequency distribution of the occurrences of ELF flashes per 6 minutes is made for the data of July and August 1965, and given in Fig. 7.

2. "ELF burst". Characteristic oscillations which usually continue for some hundred msec are named

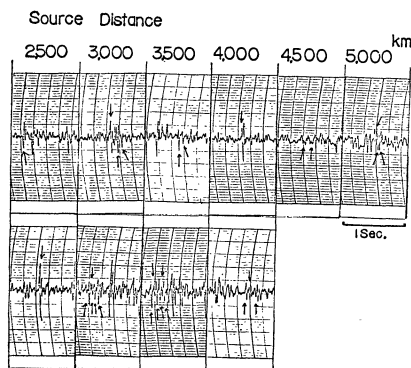


Fig. 9 Wave forms of N-type ELF bursts arranged according to their source distances from the observing station. Arrows show concurrences of two weeks.

sunrise time in the corresponding month.

ELF bursts have various wave forms which contain even single pulses. Some of the ELF bursts were followed by VLF noises while the others were not. The former was named N (noisy)-type and the latter Q (quiet)-type.

In order to estimate source distances of VLF atmospherics following N-type ELF bursts, 57 tweeks were analyzed on the sonagrams for the data of September 26–27, 1965, at Wakkanai, Kyoto and Aso respectively. The estimated source distances of the analyzed tweeks are distributed mostly between 2,500 km and 5,000 km. In Fig. 9 are shown some of the ELF wave forms corresponding to the estimated source distances. Source distances of respective pulses which make an ELF burst as shown in Fig. 9 are almost the same within error range at the evaluation of distances, and pulse intervals are around 50 msec which are of the same order as the lightning stroke intervals. It then appears that these successive pulses are from a multiple lightning strokes, and the stroke intervals would contribute to the frequency spectrum in the Schumann resonances (Raemer, 1961).

Q-type bursts are very often of larger amplitude than N-type bursts, and the numbers of occurrences of ELF bursts shown in Fig. 8 are more significantly contributed by the numbers of Q-type bursts than the N-type bursts.

3. “ELF continuous”. When the chart paper runs at the speed of 1 mm/sec, the mean amplitude of background noises can be measured by reading the width of the trace discriminated from ELF flashes and bursts. The background noises are called “ELF continuous”. It is rather difficult to find any differences in wave forms of “ELF continuous” observed simultaneously at Kyoto and Aso.

The daily variations of the mean amplitude of “ELF continuous” sampled for a few minutes every hour are shown for September 22–23 and 24–25, and December 10–11 and 14–15, 1965, March 26–27 and 30–31, and May 8–9, 1966 in Fig. 10. In Fig. 10 are also given the daily variations of the world relative thunderstorm activity for the respective corresponding month, derived from the data in Handbook of Geophysics (1960); the thunderstorm area for

ELF bursts. The numbers of ELF bursts whose amplitudes are larger than  $400 \mu V/m$  are counted.

In Fig. 8 are shown the time sequences of the numbers of occurrences of ELF bursts for September 22–23 and 24–25, December 10–11 and 14–15, 1965, March 26–27 and 29–30, and May 8–9, 1966. Average values for August 1965 are also shown in Fig. 8. It is seen in Fig. 8 that daytime values are relatively high and nighttime values relatively low. It should be noticed that there are sudden increases of occurrences at 06h in August, September, March and May, and at 07h in December respectively. These sudden increases are very characteristic and seem to be connected to the local

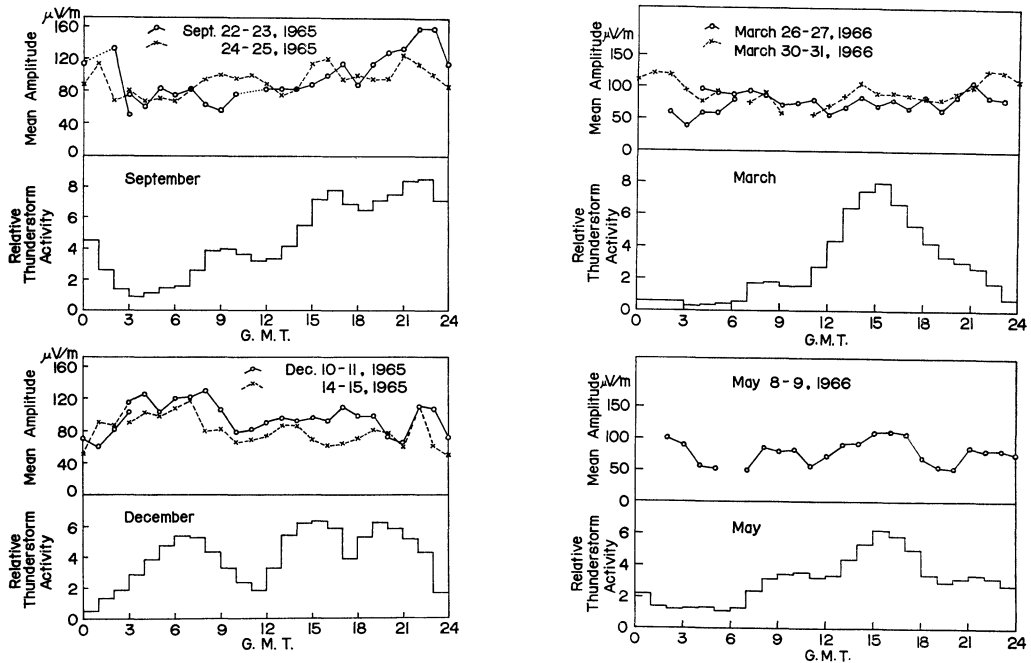


Fig. 10 Daily variations of the mean amplitude of "ELF continuous" and relative world thunderstorm activity of respective corresponding months.

every  $15^\circ$  in longitude was calculated, being multiplied by the numbers of thunderstorm days, and the values thus obtained were distributed into five hours centered at 16h local time which may be the most active time of thunderstorm in a day.

The daily variations of the amplitude of the "ELF continuous" in September and in May are very similar to the daily variations of thunderstorm activity. The maxima which occur around 09h, 16h, and 21h GMT represent the thunderstorm activity on the continents of Asia, Africa and America respectively.

The degree of the similarity of curves in December and in March to the thunderstorm activity is less than in the former cases.

## 5. Discussions

1. The measuring devices by using ball antennas described in this paper has a number of advantages. As the ball antenna has a wide frequency response, the devices can be used for the simultaneous study of both ELF and VLF phenomena. For wider frequency responses at low frequencies than those used here the value of the capacitance  $C$  should be larger although the antenna gain become less. The present measuring device is rather simple and has high gain so that it is specially suitable for portable use.

It was found, however, that long after raising antennas they were affected by highly damped air especially in the early morning, and the sensitivity of the receiving devices fell. The sensitivity calibration was made by applying voltage at 10c/s to the long metal wire stretched about 5m apart from the antennas.



The antenna constants were changed after the present experiments as follows:  $C=200\ \mu\mu F$  and  $R=2\times 10^8\ \Omega$  and the frequency response curve is added in Fig. 2. In this case the insulation is kept constant and the response at lower frequencies is highly improved.

2. Atmospheric electric field in fair-weather day subjects at land stations to large diurnal changes with double maxima and minima, one of each being in the morning and the other in the afternoon. The amplitude of the diurnal course depends largely on the wind direction and speed. If the observation is made in or near a city the diurnal amplitude is larger in the wind from the center of the city than in the wind from the suburbs by about 50%. When wind speed becomes strong the diurnal amplitude becomes smaller than when the wind speed is weak, while short period fluctuations become larger. In such air it is interesting to see the amplitude spectrum of atmospheric electric field variations in conjunction with turbulent wind speed spectrum. It was shown by Balser and Wagner (1960) that the fair-weather field component in the concerned frequency range predominates at lower frequencies than about 5 c/s. This is also approved by the present experiments.

3. ELF flashes originate from the lightning discharges occurring within the distance of about 1,000 km. In summer days a few or more thunderstorms should often occur simultaneously within that distance. It is then very peculiar that the occurrence frequencies of ELF flashes are very small compared with the occurrence frequencies of actual lightning discharges in nearby thunderstorms as shown in Fig. 7. This fact suggests that some discharges do produce ELF flashes and the others do not. This speculation was approved by the simultaneous measurements at Kyoto and Aso on August 27, 1965. At the measurements from 13 h 00 m to 13 h 06 m JST, the instrument at Aso was influenced by rather close thunderstorms and was operated at lower sensitivity than usual by 40, while at Kyoto the instrument was operated at normal sensitivity. Some of the flashes were received on both recorders, while the others were received only at Aso. The flashes received on both recorders showed simple characteristic, rapidly damping wave forms which were defined as ELF flashes in the preceding section. On July 27, 1965 a thunderstorm attacked Kyoto districts when we operated both the electrostatic field meter and ELF receiver. From the record of the field meter it was specified whether lightning discharges were within clouds or from cloud to the ground. It was found in this measurement that only cloud discharges show on the ELF records rather simple damping wave forms.

4. Characteristic features of occurrences of ELF bursts seem to be connected to their origin. It seems on first thought that N-type ELF bursts are of closer origin than Q-type bursts. It is, however, very interesting to see that Q-type bursts are very often of larger amplitude than N-type bursts. This fact should be attributed to the kind of the sources rather than distances to the sources.

Hughes (1964) showed the recorded samples of modulated oscillations which exhibit earth-ionosphere resonant frequencies which might belong to the present Q-type bursts. One of our most beautiful samples of Q-type bursts recorded at 8 h 01 m 37.6 s GMT on May 8, 1966 is shown in Fig. 11. As is seen in Fig. 11 the burst shows clear damping oscillation of about 8.0 c/s which is of the fundamental mode of the earth-ionosphere cavity resonances

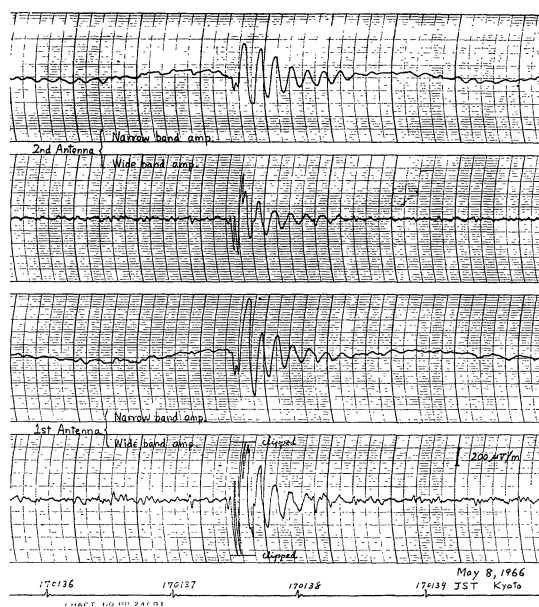


Fig. 11 The Q-type burst which occurred at 17 h 01 m 37.6 s JST (08 h 01 m 37.6 s GMT) on May 8, 1966 observed at Kyoto.

and also shows frequency dispersion. The higher frequency components at the beginning part of the burst was known on frequency-time characteristic displayed on the sonagram, extending up to some hundred c/s. The mean damping constant was estimated to be 3.3 (in the range from 2.5 to 5.0) from the record. This value is too small compared with the value of 16.3 deduced from the actual resonant frequency, 8.0 c/s and the calculated resonant frequency, 10.6 c/s for an ideal cavity with perfectly conducting boundaries (Rycroft and Wormell, 1964). It is then suggested that excitation at the origin of the phenomenon is not of pulse type but continuing energy-supply type. This type of excitation will not be produced by lightning discharge but perhaps by some other non-terrestrial origin.

Polk (1964) and Keefe, Polk, and König (1964) investigated the amplitudes and the frequency of occurrences of natural ELF magnetic field noises and they found that some imperfect correlation exists between solar flare activity and ELF noises.

On July 7, 1966 at about the time when the present study was completed an occurrence of solar flare of importance 2b was reported. On this occasion in our regular routine observation were recorded abnormal noise bursts in ELF (Ogawa, Tanaka, Miura, and Owaki, 1966). The noise frequency extended to some hundred c/s to 1 kc/s, and rather similar to that of the present Q-type bursts.

5. Holzer and Deal (1956) reported that mean diurnal variation of low-frequency (25–130 c/s) signal amplitude in March and April 1954 was strikingly similar in amplitude and phase to the diurnal variation of the atmospheric electrical potential gradient measured at sea, but during the summer months the diurnal oscillation is quite different. Balser and Wagner (1962) also reported that the mean diurnal variation of the power in the first resonance mode

during February 1961 corresponds very closely to the mean worldwide thunderstorm activity. In both cases both ELF bursts and "ELF continuous" classified in this paper would be included in their measurements. It is, however, apparent in the present investigation that the occurrences of ELF bursts rather depend on the local time while the mean amplitude variation of "ELF continuous" depends on the universal time. It seems then better to measure "ELF continuous" for the investigation in relation to world thunderstorm activity.

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### Appendix

Determination of source distances of some ELF flashes and bursts by analyzing the frequency dispersion characteristics of tweek-type atmospherics.—VLF-band atmospherics are received as tweeks as propagation conditions become good in the night; the conductivities of the earth and the ionosphere are large enough to make the wave guide, so that the electromagnetic waves propagate in the space between. Assuming that the earth's surface and the ionosphere are good conducting planes, the propagation time of TMom-wave is given by

$$t = \frac{d}{c} \left\{ 1 - \left( \frac{fc}{f} \right)^2 \right\}^{-\frac{1}{2}} \quad (1)$$

where  $d$  is source distance,  $c$  light velocity,  $f$  frequency and  $f_c$  cut off frequency which is given by  $f_c = mc/2h$  ( $m=1, 2, \dots$ ).  $m$  is the mode number and  $h$  the height of the equi-reflecting surface of the ionosphere (Iwai and Outu, 1958; Outsu, 1960). By using equation (1) various  $t$ - $f$  curves are drawn in relation to  $d$  and  $h$  as parameters. The evaluations of distances were done by fitting the calculated  $t$ - $f$  curves to the observed  $t$ - $f$  curves on the sonagrams. In the present analysis  $h$  is taken as 85 km and 90 km and  $d$  is taken every 500 km between 2,000 km and 6,000 km.

Authors dared to employ this method of sferics fixes in this paper, although this may not be very reasonable way to evaluate the distance from the origin, because how the tweek type atmospherics is produced has not yet completely be explained in view of the ionospheric reflection model.